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Resonant Operation of a Micro-Newton Thrust Stand

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Abstract

A computer automated technique suitable for evaluating micro pulsed plasma thruster (μPPT) performance has been constructed and validated in the micro-Newton (μN) force range. A swinging gate pendulum architecture oscillates with an 8 second period. Force is applied resonantly with oscillation each half period. The calibration method utilizes an electromagnet to pick up and drop masses to apply a known force in the same resonant fashion as thruster operation. The resulting equilibrium amplitudes are linearly proportional to the applied force with an intercept near zero. Thrust measurements are insensitive to short term random vibrational noise because of the resonant operation and are insensitive to long term drift because the amplitude measurements are relative, rather than absolute. The system is capable of resolving 0.5 μN over the range of 1 to 100 μN.

Introduction

While various thrust stands have been built to measure μN thrust levels, most use the steady state displacement technique[1-13]. In this method, a thrust stand at rest is displaced by the thruster force, with the record of that displacement compared to a means of calibration to determine the thrust level. Though the means of calibration and displacement measurement vary, the operating principles remain the same. The accuracy of this technique can be adversely perturbed by forces, such as thermal drift and room vibrations, because the displacement is necessarily very sensitive.

A class of force measurement systems similar to the constant displacement type is the zero-motion class of thrust stands. In this type, the lever arm position is sensed and the time derivative of position is used to drive an active damping circuit to hold the lever fixed in space. The current required to maintain zero motion is calibrated to provide force measurement; however, the same issues that apply to constant displacement measurements also apply to this class of thrust stand.

The thrust stand being discussed here operates on a different principle that minimizes the effects of external vibrations and thermal variations. It should be noted that operation and function of this thrust stand are specifically tailored to measure performance of the class of thrusters known as micro Pulsed Plasma Thrusters (μPPT's), operating at ~ 1 Hz. Rather than thruster operation displacing the indicator from the stationary reference position as in constant displacement thrust stands, this thrust stand is operated in an oscillating, undamped mode. The thruster is then fired in resonance with the swing arm oscillation, such that the thruster is engaged for half of each thrust stand period.

Because the thrust is resonantly applied with swing arm motion, the amplitude of oscillation is amplified, facilitating measurement. The motion of the swing arm behaves as a forced harmonic oscillator, with appropriately insensitive response to external vibrational forces that are either random in nature, such as people walking in the vicinity of the operating thrust stand, or are periodic but are of sufficiently different frequency that harmonics do not efficiently couple to the motion of the swing arm, such as operation of vacuum pumps.

Further, this system is insensitive to thermal drift, as long as the total swing arm motion remains in the linear range of position detection. This is due to the relative measurement of noting the difference between oscillation maxima and minima to produce swing arm total amplitude, which does not vary if the center of oscillation drifts in time. This is in contrast to a common problem associated with the constant displacement class of thrust measurements. In this case, the measurement is absolute and referenced to a position that may drift in time because of thermal variation, for example.

The insensitivity to vibration and thermal drift of the system being discussed allows for extended periods of operational usefulness. The primary benefit is the capability of providing long-term trending of thruster performance, in contrast to the labor-intensive

procedures typical for alternate thrust measuring tools that often measure single impulse events.

Milli-Newton Configuration

The vacuum chamber used for thrust measurements is 2.4 m (8 ft) in diameter with a length of 3.8 m (12.5 ft) for an internal volume of 17.2 m^3 (628 ft^3). Rough vacuum is achieved in the chamber with a roots blower, while operating pressures are maintained with two diffusion pumps using Dow Corning 704 oil. Chamber pressure before and during thruster operation is measured using an MKS cold-cathode gauge operated with a 937A MKS Gauge Controller. Chamber pressures during normal PPT operation are 3 x 10^{-5} to 6 x 10^{-5} Torr.

Thomas Haag of NASA Lewis Research Center[12,13] developed the original swinging gate thrust stand for constant displacement (100 – 500 milli-Newton) thrust measurements. In the original configuration, the thruster was mounted to an insulative phenolic plate (right hand side of figure 1) while two Lucas Aerospace 5016-600 torsional pivots supported the aluminum swing arm structure. Roll and pitch were adjusted remotely using Hurst SAS 4004-014 stepper motors without encoders. Roll and pitch location were inferred from the number of steps commanded (as displayed on the Hurst EPC-015 control units). The motors were used to move the thrust stand until the swing arm was within the linear range of the LVDT. Power and instrumentation wires are connected to the swing arm, allowing plenty of slack near the pivot flexures to minimize resistance to thrust stand movement.

After using an active damper circuit, calibrated weights (see figure 2) were applied to deflect the thrust stand. This deflection was recorded using a Servogor 111 paper strip-chart recorder, with the resulting displacements from several weights producing a calibration curve. The electromagnetic damper circuit was engaged during this entire time to minimize oscillatory motion. An example of the resulting calibration curve is illustrated in figure 3, along with typical zero drift seen during such an operation. The accuracy for this system of calibration was typically on the order of ± 1 milli-Newton. The drift in the zero point of the thrust stand and sensitivity to vibration leads to non-repeatable calibration curves and hysteresis.

Micro-Newton Configuration

This thrust stand was upgraded, including the replacement of the stepper motors with Industrial Devices Corporation P21 stepper motors with encoders. The stepper motors are computer controlled via a National Instruments MID-7604 stepper motor controller and National Instruments PXI 7344 Motion Controller card. LVDT position is digitally recorded using a National Instruments MIO 6070E PXI multifunction I/O card. A new control program operating with Windows 98© and LabView 5.1® monitors the swing arm position and calculates the maximum, minimum, and resulting average swing arm

position. To increase the swing arm amplitude due to a force input, a 5016-800 pivot with a lower spring constant replaced one of the Lucas Aerospace 5016-600 torsional pivots. Further increases in thrust stand sensitivity can be gained by replacing the remaining 5016-600 pivot as well. However, using the lower spring constant pivots reduces the maximum allowable thruster mass from 4.5 kg to 3 kg.

Micro-Newton Method

To increase the sensitivity of the thrust stand to micro-Newtons of force, the steady-state displacement method was abandoned in favor of the resonant operation method. This method intentionally oscillates the thrust stand without active damping, with the applied force (calibration or thruster) acting upon the thrust stand during the half-period of each oscillation (see figure 4).

This method has several advantages over the steady-state displacement method. First, the resonantly applied force mechanically amplifies the oscillation amplitude to an easily measurable magnitude. Second, the oscillating thrust stand is insensitive to short term vibration and third, the amplitude of oscillation is insensitive to long term drift.

Short term vibrations, such as sonic booms and foot steps, are random events whose action does not observably perturb the swing arm oscillation. Periodic vibrations, such as vacuum pump operation, occur at frequencies that do not efficiently couple energy into the swing arm oscillation due to frequency mismatch. In all cases, random and periodic vibrations do not adversely effect swing arm motion because the amplitude of interest is achieved through resonant amplification of the motion by carefully timed application of force. The period of oscillation is typically set to 8 seconds. However, this insensitivity to transient forces inhibits measurement of high frequency thrust fluctuations.

The time response of the thrust stand can be determined by examining the decay rate of the thrust stand amplitude. A typical decay rate plot is shown in figure 5 and fits an exponential curve. For example, to determine the time response for a given change to lower value in thrust, the initial operating force is matched with its corresponding amplitude from the calibration curve. This is repeated for the lower thrust value. The time difference between these two points on the amplitude decay rate curve yields the amount of time required for the thrust stand to reach the new equilibrium amplitude.

Long term drift can be problematic for continuously determining thrust when significant periods of time pass between calibrations. This issue is particularly relevant for systems in which absolute measurements are made in reference to a fixed point. Thermal change in the system is a common cause for drift error in such a system. In the resonantly applied force method, the amplitude of oscillation is determined by the difference in maximum and minimum positions of oscillation, illustrated in figure 6. This is a relative measurement and is drift insensitive, provided the total oscillation amplitude is within the linear response range of the position sensor.

The thrust stand position at any time during operation is measured by the LVDT and can be calculated in accordance with forced harmonic oscillator theory:[14]

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F(t) \qquad (1)$$

where F(t) is equal to the thrust applied for $\pi/2 < \theta < 3\pi/2$ (see figure 4) and zero otherwise.

To maximize the operating range of the oscillating thrust stand, the average location of the swing arm (max – min / 2) must be as close to zero as possible. Significant drift in the average location reduces the operating range of the thrust stand. Because the swing arm oscillates, a large linear range is necessary to ensure accurate measurement of the thrust stand position. The thrust stand includes an LVDT with a Macro Sensors TIC-9000 LVDT readout that has a linear range of ± 3.5 mm, corresponding to ± 5V LVDT output. The greater the linear range available, the greater the force that can be measured with the thrust stand for a fixed system.

Ideally, the system is configured such that the average swing arm position registers 0 V and application of a force 1.5 times that anticipated by thruster operation corresponds to ± 5 V LVDT output. This is accomplished by adjusting parameters that affect position as a function of force. One such parameter is the decay rate, which is controlled by changing flexures or draping cables of varying stiffness across the hinge line. Alternatively, the magnitude of the force component due to gravity pulling on the swing arm center-of-gravity may be adjusted by varying the angle between the gravity vector and the plane described by swing arm motion.

Calibration

Prior to performing a calibration and recording thrust measurements, an automated thrust stand balancing routine is activated. First, to ensure the maximum operating range is available for calibration and thrust measurements, the current average swing arm location is measured. If the swing arm average location is calculated to be greater than 0.090 mm away from the center, the pitch motor is automatically commanded to provide coarse adjustment. The thrust stand is sensitive to adjustments in pitch, making large changes in average LVDT location easy through commands to the pitch motor. When the average LVDT location is greater than 0.036 mm but less than 0.090 mm away from zero small changes are accomplished through use of the roll motor. This process is repeated iteratively until the average thrust stand position is within 0.036 mm of zero, ensuring maximum operating range. After this procedure, zero-point drift is minimized due to the presence of permanent magnets within the pitch and roll motors. These magnets prevent uncommanded rotation of the motors, even when the holding torque is removed.

Commanded changes in pitch and roll to the thrust stand may require re-calibration for maximum accuracy.

Once the thrust stand is centered about zero, the automatic calibration is started. The computer activates a modified (ferrous core removed) A.P.W. Co., Inc. 607R electromagnet at a 50% duty cycle to pick up the calibration mass (samarium cobalt magnet; 10 Vdc, 0.2 A). The electromagnet is suspended ~8 mm above a platter containing the calibration masses (see figure 7). Each mass is weighed using a Mettler Toledo AX105 Delta Range scale. The mass is changed through rotation of the platter so that the next mass is placed under the electromagnet. This operation is controlled automatically. The electromagnet is attached to the thrust stand by 0.13 mm (0.005 in) diameter monofilament fishing line, over a suspended aluminum pulley. The 3.38 cm (1.33 in) diameter pulley is attached to the thrust stand table via a 0.08 mm (0.003 in) diameter tungsten wire (see figure 8). Special care was taken to ensure no permanent magnets or ferrous materials were used near the electromagnet in the thrust stand structure, as this would influence the resulting force applied to the thrust stand during electromagnet activation.

Verification that the electromagnet force is acting only on the selected calibration mass and not the other masses or any other ferrous material is determined by the following technique. The first step is to disable the electromagnet power supply and excite the thrust stand to the maximum amplitude. The baseline decay of the amplitude is then measured over time. The second step is to remove the first calibration mass and disable the calibration platform motor. This allows the electromagnet to continuously act on a region of theoretically no magnetic force. The thrust stand is then excited to the maximum amplitude and allowed to decay with the electromagnet operating normally (50% of each period). The decay in amplitude is then recorded and compared to the baseline decay curve. Observation that these two decay curves are identical indicates that there is no measurable electromagnetic force acting on the thrust stand other than the selected mass during the calibration routine. All magnet control is operated by the computer system.

The magnet operation is engaged when the thrust stand is moving in the same direction as the force that will be applied from the thruster (see figure 4). While the electromagnet is powered by a BK Precision 1760 Power Supply, the precise control for this is accomplished through a National Instruments 2565 PXI General Purpose Relay Switch controlled by the same LabView 5.1® code.

The code then examines the resulting amplitude of each swing cycle. These values are stored in a data array. The last fifteen values are constantly monitored to determine if the amplitude has reached an asymptotic limit. This is determined by calculating the variation in the amplitudes over the last fifteen cycles. The variation in thrust stand amplitude is calculated as the difference between the most recent two amplitude measurements.

This variation is then stored into another array. When all of the last fifteen variation values in the array are less than a determined tolerance, convergence is assumed for the force applied and the process is repeated for the remaining calibration masses. The entire calibration process typically is complete in less than 1.5 hours. A typical time trace of amplitudes for a calibration is shown in figure 9.

A calibration curve is then created, plotting the force imparted upon the swing arm as a function of the converged amplitudes. A typical thrust stand calibration is shown in figure 10. For the masses used, sensitivity of the thrust stand is from 1 to 75 micro-Newtons. The resulting thrust stand calibration is linear described by a slope of 19.263 μN/V and an intercept of – 0.0531 μN. The corresponding quality of this curve fit has an R^2 value of 0.9997.

Error Analysis

Thrust stand calibration has three dominant sources of measurement error: 1) voltage reading from the LVDT through the Macro Sensors TIC 9000 to the National Instruments PXI 6070E multifunction I/O card; 2) error in the initial mass measurement from the Mettler Toledo AX105 Delta Range scale; 3) convergence criteria.

The Macro Sensors TIC 9000 has a voltage output linear with LVDT displacement for a range of ± 3.5 mm. Maximum voltage output for the LVDT is ± 5 volts DC. The PXI 6070E is a 12 bit volt reader card, capable of detecting ± 5 volts DC. Minimum detectable resolution for the PXI 6070E is therefore 2.4 mV. The uncertainty in the voltage measurement for the smallest converged amplitude (for the smallest calibration mass) is approximately 0.5% compared to 0.05% for the largest converged amplitude (for the largest calibration mass). For the linear range of the LVDT and the current thrust stand flexures, this corresponds to an amplitude of 1.7 micro-meters, or an approximate thrust resolution of 0.04 micro-Newtons.

The calibration masses are measured several times for a statistical average value. By increasing n, the number of measurements, this error can be reduced. Typically, n = 5 serves well for quick characterization of the four calibration masses and corresponds to an uncertainty of a few percent, which will dominate the overall calibration error. Increasing n, reduces the uncertainty and ultimately, the error may be minimized by purchasing calibration masses that are certified to a precision referenced to a NIST standard. Presently, a Mettler Toledo AX105 Delta Range scale is used, which has 0.01 mg resolution. Typically, accuracy of +/- 1.3% for forces greater than 5 μN is achievable.

The convergence criteria also influences calibration error. If the amplitude is deemed converged prior to the actual converged value, then the amplitude assigned to the applied force will be in error too low. This translates into measured thrust values that will be lower than the actual force output by the thruster being tested.

Summary

A computer automated technique suitable for evaluating micro pulsed plasma thruster performance has been constructed and validated in the micro-Newton force range. A swinging gate pendulum architecture oscillates with an 8 second period. Force is applied resonantly with oscillation each half period. The calibration method utilizes an electromagnet to pick up and drop masses to apply a known force in the same resonant fashion as thruster operation. The resulting equilibrium amplitudes are linearly proportional to the applied force with an intercept near zero. Thrust measurements are insensitive to short term random vibrational noise because of the resonant operation and are insensitive to long term drift because the amplitude measurements are relative, rather than absolute. The system is capable of resolving differences of 0.04 μN with an accuracy of +/- 1.3% for forces greater than 5 μN.

Figures

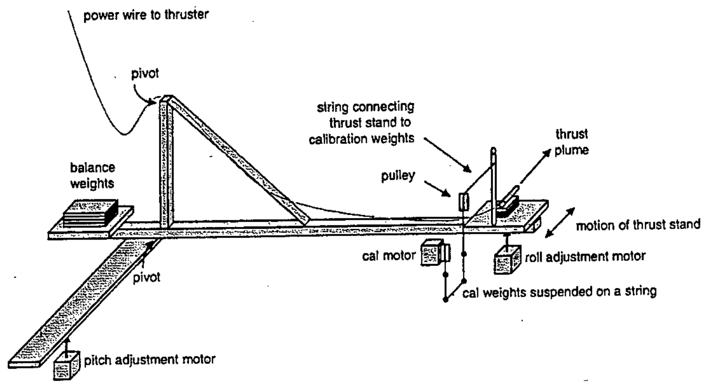

Figure 1 - Original thrust stand configuration

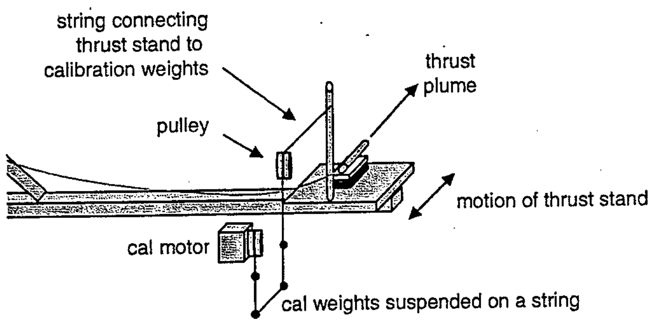

Figure 2 - Milli-Newton calibration method

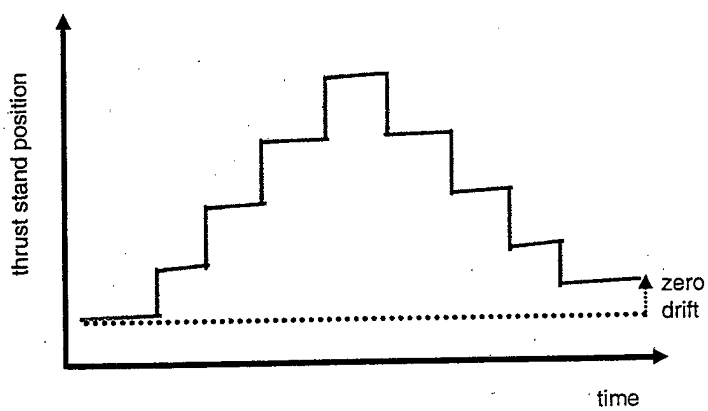

Figure 3 - Original steady state calibration result

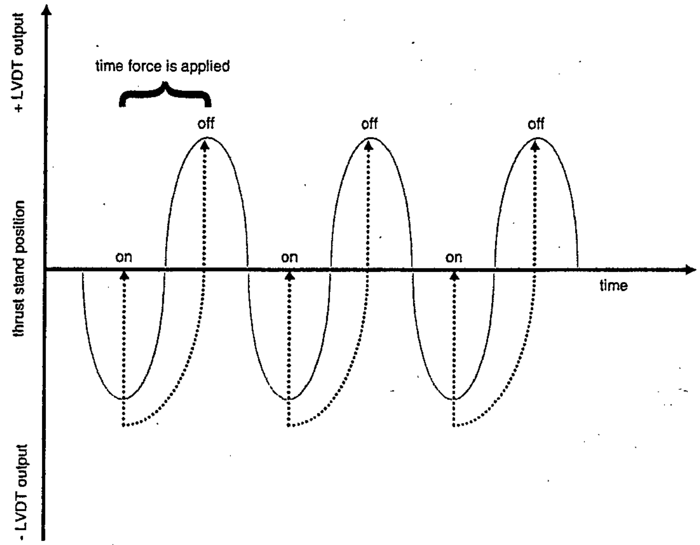

Figure 4 - Applied force duty cycle

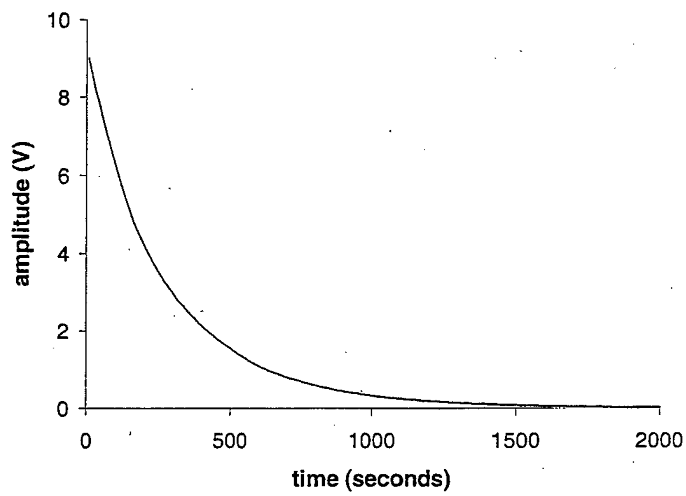

Figure 5 - Decay rate of thrust stand amplitude

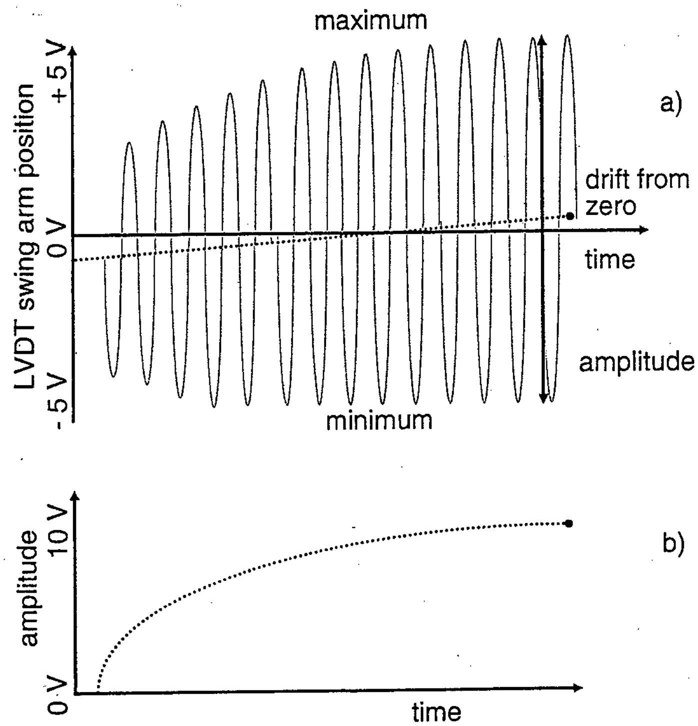

Figure 6 - Swing arm oscillation, amplitude, and long term drift shown

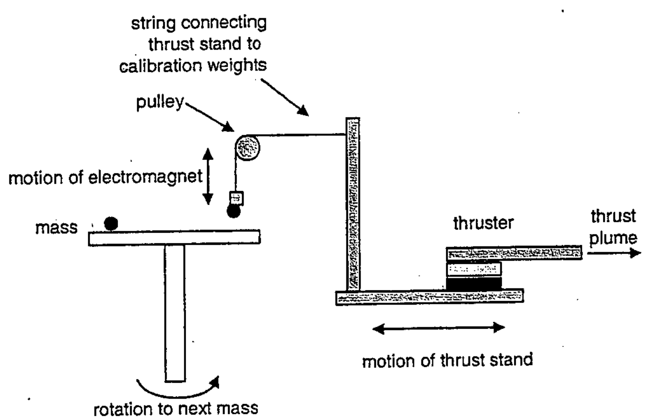

Figure 7 - Attachment of electromagnet

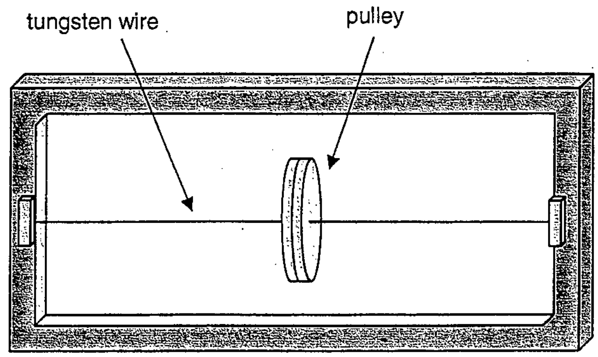

Figure 8 - Pulley suspended using Tungsten wire

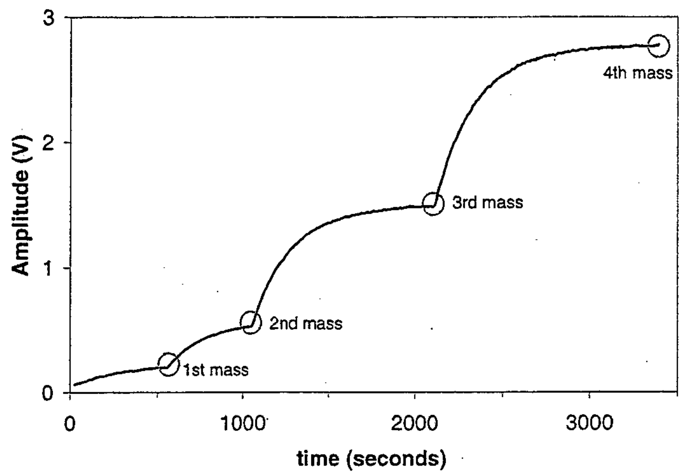

Figure 9 - Calibration mass time convergence

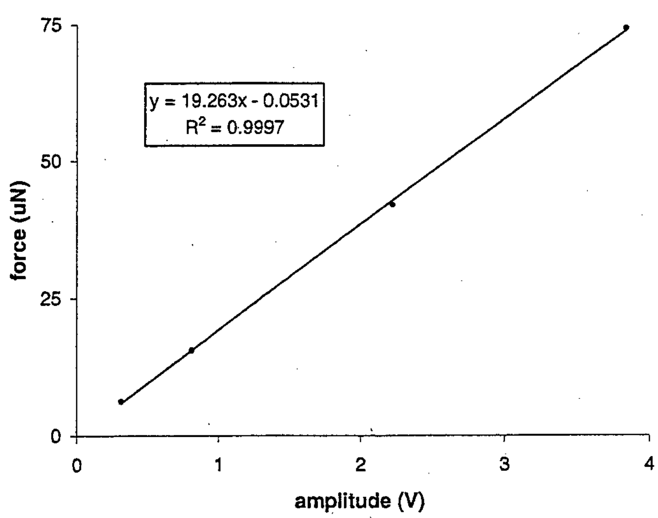

Figure 10 - Resulting linear calibration.

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